Application

For

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Title:

SYSTEM AND METHOD FOR REAL-TIME LIBRARY GENERATION OF GRATING PROFILES

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SYSTEM AND METHOD FOR REAL-TIME LIBRARY GENERATION OF GRATING PROFILES

BACKGROUND OF INVENTION

Field of Invention

Invention relates to the measurement of dimensions in gratings and more particularly to the generation and use of configurable libraries of grating profiles.

Description of Related Art

Features on semiconductor devices and transmitters of optical fiber links are being formed that are less than one micron in width. Measurement of these sub-micron features is increasingly difficult as the size of the features become smaller. However, knowledge of the dimensions of gratings or periodic structures is essential in order to determine if the dimensions of the features are within the acceptable ranges and if a particular fabrication process causes the sidewalls of the features to be tapered, vertical, T-topped or undercut.

Traditionally, a sample was cleaved and examined with a scanning electron microscope or similar device. This method is slow, expensive, and only provides one measurement number seen from the top of the feature. Angular scatterometry have been employed to measure linewidths of gratings but the process requires a setup of multiple detectors at different angles from the incident beam to measure the diffraction of the scattered light. Again, this is difficult to implement because of the setup required.

Spectroscopic reflectometry and ellipsometry are used to beam light on the grating and measure the spectra of reflected signals. Current practices basically use an empirical approach where the spectra of reflected light is measured for a known width of features in a grating. This process is time consuming and expensive even for a limited library of profiles of grating dimensions and the associated spectrum data of reflected light. There

is a need for a less laborious and less expensive method of creating the library of profiles and associated spectrum data.

Furthermore, if such a library were built for a wide range of profiles, it would be very useful to have access and use of the library in a real-time environment. An extensive library of profiles and spectrum data would however be inefficient for searching purposes needed for real-time work. For a short fabrication run, a client may only need a small subset of the extensive master library. Thus, there is a need for a method and system of providing libraries of grating profiles that are responsive to both long term and short term requirements of the client.

SUMMARY OF INVENTION

Invention resides in a method and a system for creating configurable libraries of grating profiles and spectrum data. The method comprises specifying a parameter set of a plurality of dimensions of a grating and compiling a master library of grating profiles corresponding to the combinations of the parameter set of the plurality of dimensions at different resolutions and the calculated spectrum data.

One embodiment is a system for creating a run-time library of profiles comprising a master library of profiles and the calculated spectrum data; a storage medium for storing the run-time library; a computer coupled to the master library and the storage medium; and a run-time compiler operable in the computer, for generating the run-time library; wherein the computer activates the run-time compiler to prompt for identification of the selection parameter set, to validate the selection parameter set, to extract the profiles from the master library, and to create a run-time library.

Furthermore, the present invention includes a method for evaluating grating spectrum data, the method comprising comparing a grating spectrum data to the ranges of grating calculated spectrum data in a run-time library; flagging the grating spectrum data as falling within the profile calculated spectrum data ranges in the run-time library or flagging the grating spectrum data falling outside the profile calculated spectrum data ranges in the run-time library; selecting the profile instance in the run-time library whose

calculated spectrum data is closest to the grating spectrum data; and recording the selected profile instance.

Another embodiment of the present invention is a system that invokes a compiler when a set of conditions is met. The system comprises a master library; a starting run-time library compiled with a starting set of trigger conditions; a replacement run-time library, for replacing the starting run-time library; a run-time compiler; a computer; and a comparator operable in the computer, for comparing the calculated set of process trigger values to the starting set of trigger conditions; wherein the comparator, detecting a condition where the calculated process trigger values meet the requirements of the starting set of trigger conditions, automatically invokes the run-time compiler to compile the replacement run-time library.

The present invention also includes a method of providing a service for generating a library of grating profiles, the method comprising contracting by a client and a vendor, where in return for remuneration from the client, the vendor provides access to the systems, processes, and procedures to generate the library or generates and delivers the library.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is an architectural diagram illustrating the dimensions of a grating feature in one embodiment of the present invention.

FIG. 2A is an architectural diagram illustrating the compilation of a master library of grating profiles in one embodiment of the present invention. FIG. 2B is a flow chart of the basic steps in compiling a master library of grating profiles in one embodiment of the present invention.

FIG. 3A is an architectural diagram illustrating the compilation of a run-time library of grating profiles in one embodiment of the present invention. FIG. 3B is a flow chart of the basic steps in compiling a run-time library of grating profiles in one embodiment of the present invention.

FIG. 4 is an architectural diagram illustrating the use of the run-time library to evaluate grating spectrum data in one embodiment of the present invention.

FIG. 5 is a flow chart of the process of using the run-time library to evaluate grating spectrum data in one embodiment of the present invention.

FIG. 6 is an architectural diagram illustrating the automatic compilation of a replacement run-time library in one embodiment of the present invention.

FIG. 7 is a flow chart illustrating the automatic compilation of a replacement run-time library in one embodiment of the present invention.

FIG. 8 is an architectural diagram illustrating a grating profile library generator in one embodiment of the present invention.

FIG. 9 is a flow chart illustrating the use of a grating profile library generator to generate a master library, a run-time library, and a replacement run-time library, in one embodiment of the present invention.

FIG. 10 is a flow chart of the business method of providing a service for generating grating profile libraries in one embodiment of the present invention.

FIG. 11A shows the database elements of a grating profile library in one embodiment of the present invention while FIG. 11B shows the display elements of a grating profile library in one embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENT(S)

FIG. 1 is an architectural diagram illustrating the critical dimensions (CD) of a grating feature in one embodiment of the present invention. The cross-sectional view of a feature in a grating has a grating top CD **2**, grating bottom CD **10**, a grating thickness **6**, and underlying thickness **12**. Other dimensions are the width at inflection point **8** and the height at the inflection point **14**. The inflection point **4** is the point in the sidewall of the feature where the slope changes. The percent height at inflection point is defined as the ratio of the height at inflection **14** to the grating thickness **6**. Some applications may include other feature measurements such as the magnitude of T-topping, footing,

rounding, undercut, concave sidewalls, and convex sidewalls as well as the angle of intersection of the sidewall and the underlying thickness.

FIG. 2A is an architectural diagram illustrating the compilation of a master library of grating profiles in one embodiment of the present invention. Parameter input device **16** is used to enter a parameter set including the minimum value, maximum value, and the resolution of the dimension of a grating. In alternative embodiments, a parameter set may be created by other input means and specified as the parameter set for a compilation run.

Resolution is the increment by which the parameter dimension changes for the next higher or next lower value. For example, a grating top CD may have a minimum value of 120 nanometers, a maximum value of 180 nanometers, and a resolution of 1 nanometer. Resolution steps is the number of instances of a grating dimension for a given resolution and is calculated using the following formula:

Resolution Steps (D) = ((Maximum Value - Minimum Value)/Resolution) + 1

where D refers to a dimension of a grating.

In the example above, the resolution steps of the grating top CD would be 61. The number of resolution steps is used to calculate the size of a library.

The compiler **24**, operable in the computer **18**, uses the specified parameter set to compile a master library and stores it in the output device **22**. Optionally, a master library display **20** may be produced. The computer **24** may be one computer or a server farm with a plurality of servers. The computer **24** may be co-located with the parameter input device **16** or may reside at a distributed remote site. The output device **22** may be a CD-ROM drive, a DVD drive, a disk drive, a tape drive, or a remote storage unit.

The master library comprises a matrix where the rows are profiles including an instance of a parameter dimension at varying resolutions in combination with the other parameters at varying resolutions and the corresponding calculated spectrum data. Spectrum data refers to the data representing the digitized measurements of the reflected light from a grating. Calculated spectrum data is derived by solving a rigorous

mathematical model of the reflected light from a grating with a given set of parameter dimensions. One such mathematical model is described in "An Integrated System of Optical Metrology for Deep Sub-Micron Lithography", University of California at Berkeley Doctoral Thesis of Xinhui Niu, April 20, 1999, which is incorporated here by reference.

Actual spectrum data may be obtained by using a spectroscopic optical metrology device. Examples of spectroscopic optical metrology devices include spectroscopic ellipsometers and spectroscopic reflectometers.

The size of a compiled master library is a consideration during compilation and during real-time use of the library. For example, the parameter set illustrated in Table 1 would generate a total master library size of 13, 177,728 profiles, representing the combinations of the parameter-dimensions listed in the table at varying resolutions. The size of the library is calculated by multiplying the resolution steps of each dimension, in the above case, the library size is equal to (16*81*31*4*41*9). The first and last three profiles of a master library compiled with the parameter set of Table 1 would be:

Grating Top CD	Grating Bottom CD	Grating Thickness	Percent Height at Inflection Point	Grating Width at Inflection Point	Underlying Thickness	Spectrum data
120	160	220	0.6	140	2.3	$Spectra_1$
120	160	220	0.6	140	2.5	$Spectra_2$
120	160	220	0.6	141	2.3	$Spectra_3$
...	...	...	...	...	...	...
180	200	250	0.9	179	2.5	$Spectra_{n1}$
180	200	250	0.9	180	2.3	$Spectra_{n2}$
180	200	250	0.9	180	2.5	$Spectra_{n3}$

At about 1.5 seconds per profile, the master library of Table 1 would take a server farm of 128 processors about 7 days of CPU time to generate and compile.

FIG. 2B is a flow chart of the basic steps in compiling a master library of grating profiles in one embodiment of the present invention. Initially, the parameter set of a plurality of dimensions for a grating is specified **110**. In one embodiment, the parameter set may be specified by entering the parameters through an input device such as a terminal or PC or it may be specified by identifying a pre-existing file available to the compiler. The pre-existing file may be a file transmitted to the computer or a remote file

accessible to the computer. Next, the compiler compiles a master library of grating profiles based on the specified parameter set **125**. The specified parameter set is edited to ensure the minimum value, maximum value, and the resolution of the dimension are within the ranges established for the application. For example, in one embodiment, the dimensions must be expressed in nanometers. Next, the master library is stored in a storage medium **130**.

FIG. 3A is an architectural diagram illustrating the compilation of a run-time library of grating profiles in one embodiment of the present invention. The system configuration is similar to FIG. 2A. The parameter input device **38** is used to enter a parameter set for the creation of a run-time library **32** from the master library **36**. In alternative embodiments, a parameter set may be created by other input means and specified as the parameter set for a compilation run. The run-time compiler **40**, operable in the run-time computer **30**, edits the parameter set to ensure application edit rules are followed, and creates the run-time library **32**, optionally creating a run-time library display **34**. The run-time library **32** may be stored in a storage medium such as a CD-ROM, a DVD, a disk, a tape, or a remote storage. The computer **30** may be co-located with the parameter input device **38** or may reside at a distributed remote site, accessible to the input device **38** through a public network or dedicated communications lines.

FIG. 3B is a flow chart of the basic steps in compiling a run-time library of grating profiles in one embodiment of the present invention. Initially, the parameter set for run-time library is specified **200**. Table 2 is an example of a parameter set for compiling a run-time library. In one embodiment, the parameter set may be specified by entering the parameters through an input device such as a terminal or PC or it may be specified by identifying a pre-existing file available to the run-time compiler. The pre-existing file may be a file transmitted to the computer or pre-existing file may be a remote file accessible to the computer. The parameter set is validated **210** by applying the application edits. In one embodiment, the run-time compiler edits the parameter set to ensure that the minimum and maximum values of the dimensions are within the ranges of the same dimension in the master library. The parameter set is also edited to ensure that

the resolution is not lower, (i.e., finer resolution) than the resolution used in the master library and that the resolution is a multiple of the resolution used in the master library. Table 3 is an example of a parameter set for compiling a run-time library showing error messages in specifying the resolution. Next, the run-time library is compiled based on the edited parameter set **220**.

FIG. 4 is an architectural diagram illustrating one embodiment using the run-time library to evaluate grating spectrum data. A spectroscopic optical metrology device **50** provides grating spectrum data to profiler application server (PAS) **60**. The profiler application server **60** accesses the run-time library **58** to compare instances of the library with the spectrum data from the spectroscopic optical metrology device **50**. An exception file **54** or an exception display **56** may be created.

FIG. 5 is a flow chart of the process of using the run-time library to evaluate grating profile data in one embodiment of the present invention. The spectrum data of a grating is collected **300**. The collected data may come from spectroscopic optical metrology devices operating real-time or may be from a file containing such data. The spectrum data is received by the profiler application server **310**. The profiler application server accesses the run-time library of grating profiles **320** and determines, based on application criteria, if the grating spectrum data is within the run-time library calculated spectrum data ranges **320**. If the grating spectrum data is outside the run-time library calculated spectrum data ranges, flag the grating spectrum data **330.** Alternatively, if the grating spectrum data is within the run-time library calculated spectrum data ranges, flag the grating spectrum data **340** and select the profile instance that has the calculated spectrum data closest to the grating spectrum data being examined **350**. The closest library spectrum data is one that minimizes the error between the grating spectrum data and the library calculated spectrum data. Several optimization procedures are available to minimize the error, such as simulated annealing, described in "Numerical Recipes," section 10.9, Press, Flannery, Teulkolsky & Vetterling, Cambridge University Press, 1986; which is incorporated by reference. The error metric that produces appropriate results is the sum-squared-difference-log error, where the optimization procedure

minimizes the error metric between the grating spectrum data and the library spectrum data.

For example, this process would flag a grating with spectrum data outside the run-time library ranges, due to process drift. Conversely, a grating that is within the run-time library ranges may be flagged, depending on the options chosen for the application.

FIG. 6 is an architectural diagram illustrating the automatic compilation of a replacement run-time library in one embodiment of the present invention. A data entry device **38** is used to enter data processed by the trigger processor **80**, which creates a starting trigger file **76**. For example, a trigger file may contain data indicating a replacement run-time library **84** is required if the process average change of the grating bottom CD is more than 0.5 after a certain number of manufacturing runs, where:

$$\text{Process average change (D)} = (\text{Library Process Average}_{(D)} - \text{Actual Process Average}_{(D)}) \div (\text{Library Dimension Range}_{(D)}/2)$$

where

$$\text{Library Process Average}_{(D)} = (\text{Library Maximum Value}_{(D)} + \text{Library Minimum Value}_{(D)}) / 2;$$
$$\text{Actual Process Average}_{(D)} = (\text{Actual Maximum Value}_{(D)} + \text{Actual Minimum Value}_{(D)}) / 2;$$
$$\text{Library Dimension Range}_{(D)} = (\text{Library Maximum Value}_{(D)} - \text{Library Minimum Value}_{(D)});$$

and D is the grating dimension.

A spectroscopic optical metrology device **50** collects grating spectrum data and sends this data to profiler application server **60.** The profiler application server **60** selects the profile instance from the starting run-time library **58** that has the calculated spectrum data closest to the grating spectrum data from the spectroscopic optical metrology device **50.** Depending on the implementation options, the profiler application server **60** may send the grating dimensions data of the selected profile instance from the starting run-time library **58** immediately to the comparator **82** or accumulate the grating dimensions data and wait until a certain period of time has elapsed or until after a predetermined number of manufacturing cycles is completed or until a trigger condition is encountered. The comparator **82** processes the starting trigger file **76** created by the trigger processor

80 and the real-time or batch data dimensions from the profiler application server **60**. If the trigger conditions are met, the comparator **82** invokes run-time compiler **40** to generate a replacement run-time library **84**. The comparator **82** also creates a replacement trigger file **78** to be used as the starting trigger file in the next auto compilation cycle. The run-time compiler **40** uses the master library **36** as input, the data from the comparator **82** and the starting parameter set **88** to create the replacement run-time library **84** and to create a replacement parameter set **89**. The replacement parameter set **89** becomes the starting parameter set in the next auto compilation cycle. In an alternative embodiment, the profiler application server **60** and the computer **86** may be a single computer device.

FIG. 7 is a flow chart illustrating the automatic compilation of a replacement run-time library in one embodiment of the present invention. Based on the application, the client selects one or more trigger conditions that must be met for an auto-compilation to be invoked. This starting set of trigger conditions is specified **400**. Grating spectrum data is received and the profile instance from the starting run-time library that has the calculated spectrum data closest to the grating spectrum data is selected **410**. The starting trigger condition values are evaluated when the application criteria require the evaluation to be done **420**. For example, the application criteria may require evaluation of the trigger condition values after a specific number of manufacturing runs are completed or when a predetermined time interval has elapsed. The starting trigger conditions are compared to the starting trigger condition values and if the conditions are met **430**, a replacement trigger file and a replacement run-time parameter set are created **440**. The replacement run-time library is compiled based on the replacement run-time parameter set **450**. The replacement trigger file is set as the starting trigger file and the replacement parameter is set as the starting parameter set **460**.

For example, a run-time library is compiled with the grating bottom CD having a minimum value of 180 nanometers (nm) and a maximum value of 200 nm; thus, the run-time library has a bottom CD process average of 190 nm, (180+200)/2. The starting set

of trigger conditions entered for this application is that a replacement run-time library is compiled anytime the change in the grating bottom CD process average exceeds 0.5. After a manufacturing run of 2,000 wafers, the comparator **82** detected that the calculated actual process average for the grating bottom CD changed from 190 nm to 183 nm due to process drift. The grating bottom CD process average changed by 0.7, as shown in the following calculation:

$$\text{Process average change (Bottom CD)} = [(190-183) \div (200-180)/2] = 0.7.$$

Since the bottom CD process average change of 0.7 is greater than the trigger condition of 0.5, the comparator **82** would invoke the run-time compiler **40** to use the starting parameter set **88**, create a replacement parameter set **89** with the grating bottom CD having a minimum value of 173 nm and a maximum value of 193 nm. A replacement run-time library **84** would be compiled by the run-time compiler **40** using the replacement parameter set **89** and the master library **36** as input. The comparator **82** would create a replacement trigger file **78** with a process average of 183 nm. If after another manufacturing run of 1500 wafers, the comparator again detected a shift of the grating bottom CD process average, the process of evaluating the trigger condition values and compilation of the replacement run-time library would be repeated. Table 4 is the example of a replacement parameter set created for the automatic compilation of the run-time library, triggered by the change in the grating bottom CD process average exceeding 0.5.

FIG. 8 is an architectural diagram illustrating a grating profile library generator. A requestor device **92** sends a request for a grating profile library to the library generator **94** operable in computer **98**. The library generator **94** creates the library and stores the library in output device **96** and sends a response to requestor device **92**. The requestor device **92** and the output device **96** may be located in separate remote locations from the computer **98**. The links between the requestor device **92** and the output device **96** to the computer **98** may be a network, such as the Internet. The computer **98** may be one

computer or a server farm. The requestor device **92** and the output device **96** may be in the same unit.

FIG. 9 is a flow chart illustrating the use of a grating profile library generator to generate a master library, a starting run-time library, and a replacement run-time library, in one embodiment of the present invention. A request for generating a type of grating library is entered **500**. The library type entered in the request is determined **510**. If the request is for a master library, the master library is compiled **520**; if the request is for a run-time library, the run-time library is compiled **530**, otherwise if the request is for a replacement run-time library, a replacement run-time library is compiled **540**. In all cases where there is a successful compilation, the compiled library is stored in a storage medium or a file is created for network processing **550**, where the stored library is transmitted to the client or downloaded by the client.

FIG. 10 is a flow chart of the business method of providing a service for generating grating profile libraries in one embodiment of the present invention. The client and the vendor contract for the vendor to provide a service regarding grating profile libraries **600**. The type of service contracted may be a network service, package service or product service **610**. For a network service, an account is created for the client by the vendor to provide library generation service through a network **620**, such as the Internet. For a package service, the vendor provides a package of software, procedures, and or hardware to the client **630**. For a product service, the vendor obtains information for the type of library desired and the vendor provides the generated library product **640** to the client. The client may be an organization with many agents, assignees, or licensees. In all instances, the vendor obtains remuneration for the services provided **650**.

FIG. 11A shows the database elements of a grating profile library while FIG. 11B shows the display elements of a grating profile library.

There are many advantages for the current invention. The creation of the master library allows a one-time generation of wide ranges, resolutions, and shapes of grating profiles and associated spectrum data, without the need for the laborious empirical measurements. The creation of a run-time library allows for the generation of the specific

geometries and shapes of the grating profiles needed for a specific manufacturing window. The size of the run-time library is kept small to facilitate quick search times. Fabricators can re-center their libraries into smaller dimensions or make minor changes to the underlying thickness and get the library response time required for real-time work.

Foregoing described embodiments of the invention are provided as illustrations and descriptions. They are not intended to limit the invention to precise form described. In particular, it is contemplated that functional implementation of invention described herein may be implemented equivalently in hardware, software, firmware, and/or other available functional components or building blocks.

Other variations and embodiments are possible in light of above teachings, and it is thus intended that the scope of invention not be limited by this Detailed Description, but rather by Claims following.

Parameter	Minimum, nanometer (nm)	Maximum, nanometer (nm)	Resolution, nanometer (nm)
Grating Top Critical Dimension (CD)	120	180	1
Grating Bottom CD	160	200	0.5
Grating Thickness	220	250	1
Percent Height at Inflection Point	0.6	0.9	0.1
Grating Width at Inflection Point	140	180	1
Underlying Thickness	2.3	2.5	0.2

TABLE 1 - Parameter Set for Compiling a Master Library

Parameter	Minimum, nm	Maximum, nm	Resolution, nm
Grating Top Critical Dimension (CD)	140	160	1
Grating Bottom CD	180	200	0.5
Grating Thickness	230	240	1
Percent Height at Inflection Point	0.8	0.9	0.1
Grating Width at Inflection Point	150	170	1
Underlying Thickness	2.3	2.5	NA

TABLE 2 - Parameter Set for Compiling a Run-Time Library

Parameter	Minimum, nm	Maximum, nm	Resolution, nm
Grating Top Critical Dimension (CD)	140	160	1
Grating Bottom CD	180	200	0.25 Resolution too high
Grating Thickness	230	240	1
Percent Height at Inflection Point	0.8	0.9	0.25 Resolution is not a correct multiple
Grating Width at Inflection Point	150	170	1
Underlying Thickness	2.3	2.5	NA

TABLE 3 - Parameter Set for Compiling a Run-Time Library Showing Edit Errors

Parameter	Minimum, nm	Maximum, nm	Resolution, nm
Grating Top Critical Dimension (CD)	140	160	1
Grating Bottom CD	173	193	0.5
Grating Thickness	230	240	1
Percent Height at Inflection Point	0.8	0.9	0.1
Grating Width at Inflection Point	150	170	1
Underlying Thickness	2.3	2.5	NA

TABLE 4 - Replacement Parameter Set for Automatic Compilation of a Run-Time Library Triggered by a Change in the Grating Bottom CD Process Average Exceeding Trigger Conditions